FRACTURE MECHANICS AND METALLOGRAPHIC ANALYSIS OF THE DEFECTS IN A GENERATOR ROTOR AFTER 190000 HOURS OF SERVICE

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A generator rotor was scrapped after 190,000 hours of service and 255 cold start-ups, due to the high number of large defects detected by in-service boresonic inspection. Metallographic and fractographic analyses of defects and mechanical tests in the defect-free regions were performed. The results were used to evaluate according to LEFM theory the possibility of the largest defects to grow under the fatigue loads induced by start-ups. A negligible growth was calculated even for the largest defect; only some local linkage of original shrinkage cavities could have taken place. The outcomes of this study encourage similar analyses to be performed on flawed components, in order to assess the feasibility of further operation.

INTRODUCTION

The service life of old generator rotor forgings can be strongly limited by the presence of defects due to the limits of the existing technology at the time of manufacture. NDT methods nowadays allow to detect these defects with in-service inspections, in order to evaluate the risks of continued operation, and eventually decide some local repair or the replacement of the rotor.

In this paper, the analyses performed on a scrapped generator rotor are presented and discussed, with the aim of focusing the methodologies which could be used in future cases of rotor life assessment.

The rotor under examination was built in 1957 and subjected to a peripheral ultrasonic inspection in the as-received condition; no indication of significant defects was obtained. A further endoscopic inspection detected a few defects in the axial bore region; they were eliminated by local grinding.

In 1978, the rotor underwent the first in-service boresonic inspection, after 130000 hours of service; so many defects were found that the bore was overbored

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from 78 to 110 mm in diameter; moreover, local grinding was performed on the surface of the new bore to eliminate the remaining surface defects. The rotor was subsequently returned to service. In 1987, after 190000 hours of service and roughly 255 cold start-ups, the rotor underwent another boresonic inspection. A rather critical defectology was revealed, due to the improvement of the inspection technique; the component was replaced.

The experimental activities were performed both on "low defect" and "high defect" zones. In the first case, the aim was to characterize the microstructure and the mechanical properties of the material of the rotor (NiCrMoV type steel); in the latter case, metallographic and fractographic analyses of the largest defects were performed, in order to determine their actual size (to check NDT indications), their nature and possible evolution.

MATERIAL AND EXPERIMENTAL

The sketch of the generator rotor on which the experimental campaign was carried out is shown in Figure 1. The chemical composition of the material sampled from the bore and the periphery are reported in Table 1. Tensile properties are given in Table 2.

In the "low defect" regions, the following metallographic techniques were used: microstructure determination, microanalysis of the segregation bands, examination of the inclusion state, PAE (Picric Acid Etch) tests, Auger spectroscopy; moreover, hardness and microhardness measurements were performed. The mechanical characterization consisted of tensile, impact, static toughness and fatigue crack growth tests; some of the broken specimens were eventually subjected to fractographic investigations. Finally, residual stress determination was performed with the hole-drilling strain-gage method.

In the "high-defect" regions, stratigraphic examinations of some significant defects were carried out, in order to compare their actual lie, dimension and location with the indications given by the boresonic inspections; moreover, fractography of samples containing the largest defects, broken in liquid nitrogen

TABLE 1 - Chemical composition (weight %) of the rotor, measured in the bore region (sample 1) and in the periphery (sample 2).

Sample	C	S	P	Al	Si	Ti	V	Cr
1	0.30	0.018	0.007	0.035	0.283	0.001	0.044	1.327
2	0.33	0.020	0.011	0.030	0.266	0.001	0.045	1.329

Sample	Mn	Cu	Ni	Mo	Sn	Sb	N_2	O_2
1	0.334	0.232	2.317	0.385	0.027	0.010	0.0099	0.0163
2	0.338	0.226	2.324	0.388	0.027	0.011	0.0104	0.0226

TABLE 2 - Tensile properties measured on the rotor at room temperature in the tangential direction.

Rotor zone	S_y, MPa	S_u, MPa	El_t, %	Z, %
Bore	688	875	13	37
Periphery	724	911	12	37

or by fatigue, was performed in order to determine their nature and evolution.

Finally, a theoretical evaluation from the viewpoint of LEFM was pursued in order to define the amount of fatigue crack growth experienced by the main fabrication defects and caused by operation.

RESULTS AND DISCUSSION

The chemical composition showed no abnormal variations among different zones of the forging. Contents of minor elements (Si and particularly P and S) were appreciably higher than the nominal values, and J-factor (1) values above 200 were calculated, indicating that the material is prone to temper embrittlement.

The microstructure (bainitic), the grain size (average: 38 microns) and the segregation fine grained bands were typical of this class of materials.

Apart from minor variabilities related to test temperatures, orientations and sampling regions, material flow stress was about 30% higher than nominal, and tensile ductility 10% lower than the minimum requirement for this steel; an unexpected feature emerged from tensile tests, in that the ductility (El_t and Z) measured at the bore in T direction showed a reduction at 70 °C (El_t = 8% and Z = 27%) with respect to RT values in Table 2. No rationale could be given to this decrease; interestingly, it was not the first time that a similar trend was observed by ENEL on service exposed material (2).

The material $FATT_{50}$ was located in the interval 84÷94 °C (lower value indicative of bore material), i.e. rather high, and in agreement with the the 1978 investigation (as expected, since at the very moderate operating temperature of this component no shift of the $FATT_{50}$ can occur). From the PAE tests, estimates for $\Delta FATT_{50}$ in the range 52÷65 °C were calculated (3). The cause for this shift, producing the somewhat high final value of $FATT_{50}$, is probably due to the initial heat treatment operations on this component.

Fatigue Crack Growth (FCG) tests were performed at R.T. on 1"-thick Compact Tension specimens, sampled from regions reasonably free from inclusion clusters and shrinkage cavities, using R-ratio=0.1, test frequency of 20 Hz and the Potential Drop technique to monitor crack propagation. FCG data in the range $\Delta K > 25$ MPa$\sqrt{m}$ revealed higher crack propagation rates with respect to data obtained in similar tests on steels of this class (4), Figure 2. The Paris curve was then used to estimate periods of safe crack growth, on the basis of the actual maximum defects revealed by NDT and the calculated values of cyclic stresses, as indicated below.

From microscopy observations of the regions where previous boresonic inspections had revealed the presence of defects, it was possible to conclude that those indications, that might be suspected to be cracks and must be treated as cracks in the integrity analysis of the component, were actually inclusion clusters (mainly MnS, Figures 3a and 3b) and shrinkage cavities (Figure 3c) formed during ingot solidification. Fractographical evidence of fatigue crack extensions (i.e. striations) was found only in very local areas, suggesting that fatigue loading was likely to cause interlinkage of already existing defects (Figure 3d), in regions where high ΔK values were present due to local stress intensification caused by particular geometrical asperities of the defects. This cracking phenomena did not propagate into the defect-free material (note that FCG data in Figure 2 refer to defect-free material), where indeed no evidence of transgranular fatigue cracking was ever observed.

The absence of large scale crack growth was confirmed by calculations based on the Paris law data mentioned above. The most severe defect (revealed by NDT and confirmed by the direct destructive observations) was considered, being at the bore, with a radial depth of 30 mm and a surface length of 120 mm. This "equivalent" semielliptical crack was embedded in a tangential stress field varying from 0 (off-service) to 160 MPa (centrifugal forces during operation); this maximum value was chosen taking into account that the most serious defects were not located in the periphery of the rotor, where torsional stresses as high as 300 MPa would be acting during operation. The largest value obtained for ΔK was 49 $MPa\sqrt{m}$. Assuming such costant ΔK level active on that largest crack during the elapsed 255 cycles of the component, a total propagation length of 1.1 x 10^{-3} mm was obtained. Even if an acceleration as high as 50 times was assumed for the few weak areas, the crack growth would only be 50 microns.

It is worth pointing out that this is a very conservative estimate, coming from the maximum of several K estimation formulas and the strong crack idealisation: 2-D, straight, single, sharp crack geometry, in contrast to typical geometries of inclusions and shrinkage cavities, with blunted tips, multiple branching on several planes, crack faces connected by unbroken bridges. The assumed stress field, as already stated, also accounted for the location and orientation of the most serious defects, all found in the bore region. Moreover, the direct measurements of the residual stress field via the drilled hole method revealed compressive stresses in bore region (about 50 MPa), and this is a further feature shielding crack propagation. The above finding of no fractographical evidence of cracked regions, except for a few interlinkage zones where abnormally high ΔK levels could be reached, seems therefore confirmed.

CONCLUSIONS

1. The material is in a rather brittle condition, but this is not due to service. The fatigue crack growth data experimentally obtained in tests on specimens sampled from the defect-free regions are significantly larger than similar materials' data.
2. The observation of saw-cut sections of the rotor substantially confirmed the findings (position and extension of the defected areas) of the previous boresonic inspections, on which the withdrawal decision was based.
3. The defects were found to be inclusion clusters and shrinkage cavities, i.e. existing prior to service.
4. Subcritical crack growth due to fatigue mechanisms was observed to occur only in local areas, as an interlinkage between adjacent defects.
5. On the other hand, a conservative estimate of the maximum extent of fatigue cracking for the most severe defect found in the rotor predicts a very low value of crack extension during the 255 start-stop cycles undergone by the component. Therefore, apart from the few interlinkages between the adjacent inclusion clusters and shrinkage cavities, the resulting defects may be subsequently regarded as frozen during service.
6. The poor microstructure of this material was not totally surprising, seeming representative of many old Italian forgings, of the '50s production. Based on the modest level of the stress fields acting in the defected areas, the present outcomes support the idea that the decision taken in 1987 to positively retire that component from service was rather conservative, as further operation (of course with some heavier periodic component monitoring, to reduce risk of accidents) was a viable cost-effective solution.
7. As a general final comment, it can be stated that the high levels reached presently in the fields of experimental techniques, modelling methods and basic knowledge of phenomena related to structural materials for long term plant operation make possible a more confident (efficient) use of the components.

SYMBOLS USED

S_y	=	yield strength (MPa)
S_u	=	ultimate tensile strength (MPa)
El_t	=	total elongation at fracture for a tensile specimen (%)
Z	=	reduction of area at fracture for a tensile specimen (%)
$FATT_{50}$	=	Fracture Appearance Transition Temperature corresponding to 50% shear fracture (°C)
K	=	stress intensity factor (MPa$\sqrt{m}$)

ΔK = cyclic range of the stress intensity factor ($MPa\sqrt{m}$)

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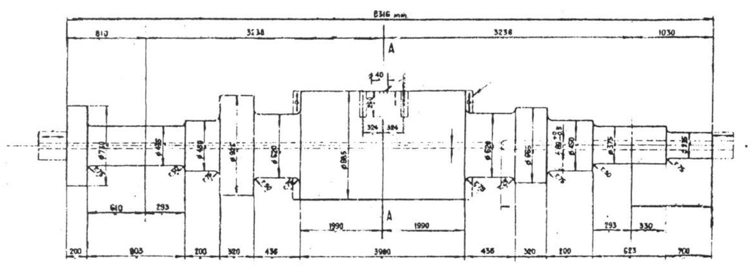

Figure 1 Sketch of the generator rotor.

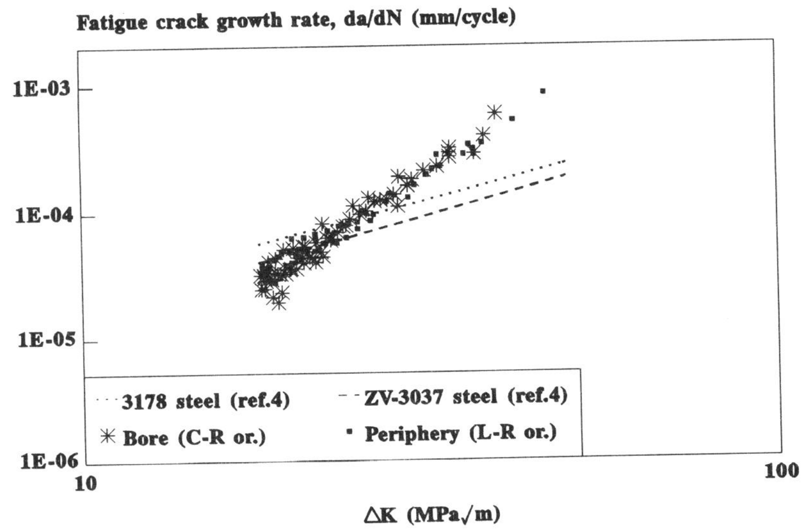

Figure 2 Comparison between trend of FCG data measured on the generator rotor in the Paris' regime and those reported in ref. (3) [R-ratio = 0.1].

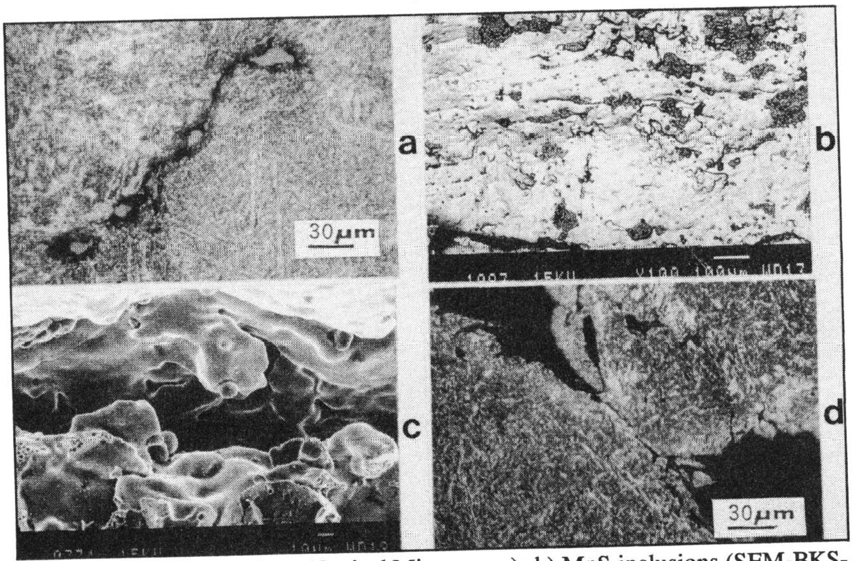

Figure 3 a) MnS inclusions (Optical Microscope); b) MnS inclusions (SEM-BKS-COMPO); c) Shrinkage cavities (SEM); d) Example of linkage (Opt. Micr.).